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Event-triggered model predictive schemes for freeway traffic control

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ABSTRACT

Objective of the paper is to define a new freeway traffic control approach based on the Model Predictive Control methodology. The control strategy adopted is ramp metering, which is able to reduce the flow entering the mainstream from the on-ramps so as to enforce traffic regularity. To determine the ramp metering actions, an innovative MPC scheme is proposed and is characterized by two major novel aspects. First of all, the finite horizon problem to be solved has a mixed-integer linear form, so that efficient solvers can be used to find the optimal solution. Secondly, in order to reduce the number of computations, the proposed MPC scheme is of event-triggered type, i.e. the control law is not updated at each time step but only when a given set of conditions is verified. The proposed scheme is assessed in the paper via simulation showing its effectiveness in different traffic scenarios.

1. Introduction

Freeway networks are complex systems that have been studied by researchers for some decades, in particular as regards the definition of appropriate control approaches. Even though the traffic control methods present in the literature have been normally devised in order to reduce congestions, as highlighted in the overview paper by Papageorgiou (2002), this is not the only possible objective of traffic control. For instance, the increase of safety or the minimization of traffic emissions could be goals to be sought primarily (see the works by Lee et al. (2006), Zegeye et al. (2013), Pasquale et al. (2013)) or, at least, to be explicitly considered.

One of the most widely studied and applied control strategies for freeway traffic control is ramp metering, which adopts traffic lights at the on-ramps in order to reduce the traffic flow entering the freeway (Papageorgiou and Papamichail, 2008). The main relevant applications of ramp metering date back to the Nineties, when the feedback traffic controller ALINEA (Papageorgiou et al., 1991) was firstly introduced. From then, different ramp metering control approaches have been developed, in some cases coordinated with variable speed limit control. Among them we can cite for instance the proportional-integral version PI-ALINEA proposed by Wang et al. (2010), the non-linear Model Predictive Control (MPC) frameworks adopting METANET as a prediction model proposed by Bellemans et al. (2006) and Hegyi et al. (2005), the optimal mainstream traffic flow controller described in Carlson et al. (2010), the MPC scheme using the Cell Transmission Model for the prediction developed by Ferrara et al. (2012), or the optimal freeway ramp metering approach based on the Asymmetric Cell Transmission Model proposed by Gomes and Horowitz (2006).

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The traffic control schemes based on MPC are very effective thanks to the possibility of predicting the system behavior, but they are in general highly demanding from the computational point of view. In fact, every control interval, it is necessary to solve a finite horizon optimal control problem (FHOCP) which is often non-linear and in which the number of variables involved can be very large. Three main issues affect the practical applicability of MPC schemes for freeway traffic control. Firstly, a non-linear optimal control problem for a large scale system must be faced. Secondly, this highly complex problem must be solved every control interval, i.e. a high number of times. Finally, the scheme involves the need of transmitting the system state measurements and the control signals to actuators every control interval (then, again, a high number of times). Depending on the available technological infrastructure, the previous three issues can have a different impact on the applicability of the control scheme, that anyway turns out to be critical from the practical point of view.

Consequently, the on-line application of MPC schemes is suitable only in small networks, as highlighted also by Frejo and Camacho (2012) that propose local techniques, with a suboptimal behavior, but able to be implemented in real time. The difficulty of applying real-time MPC schemes to large traffic networks is also highlighted by Ghods et al. (2012) that adopt an approach based on game theory and distributed controllers in order to cope with the high amount of information and computational resources required to implement high-quality traffic control schemes in large freeways. In order to control large freeway networks, some distributed MPC algorithms have been developed (see for instance Ferrara et al. (2014), Majid et al. (2014)). In other approaches, in order to reduce the complexity of the MPC schemes and hence to develop solutions to be applied on-line in large networks, the nonlinear optimization problems are properly relaxed to be linear, as done for instance by Muralidharan and Horowitz (2012) who adopt the so-called Link-Node Cell Transmission Model.

The idea underlying the present work is to define an innovative predictive control scheme in which the computation effort is reduced with respect to classical MPC schemes. First of all, in the proposed approach the FHOCP is conveniently formulated as a mixed-integer linear mathematical programming problem that can be solved optimally with efficient commercial solvers. Secondly, the proposed MPC scheme is of event-triggered nature. This means that a triggering condition based on measurements of the system state is verified at any time step and, only when it is satisfied, the control law is re-computed. Preliminary versions of the proposed event-triggered scheme can be found in Ferrara et al. (2012) and Ferrara et al. (2013), where however the objective of the control scheme is different, since the deviations of the system variables from their equilibrium values are minimized quadratically (giving rise to a mixed-integer quadratic programming problem, whereas in this paper the problem is linear). With the considered event-triggered control scheme, the computational effort is reduced, i.e. there is a reduction in the number of times the FHOCP is solved. Consequently, this control scheme is characterized by a reduction of data transmissions over the network, since there is a decrease in the number of times the control law has to be communicated to actuators. This data transmission reduction is not the main aim of this work but it represents an advantageous characteristic of the proposed control scheme.

The concept of event-triggered strategies, in which the sampling is event-triggered rather than time-triggered, is quite new in the literature and has been conceived in order to reduce the energy, computation and communication effort, that is a crucial point in modern large-scale control systems. Event-triggered control laws have been studied basically for continuous-time systems (see the work by Heemels et al. (2012) and the references therein). Some approaches have been also developed for discrete-time systems (as, e.g., in Eqtami et al. (2010, 2011)). Some works in the literature combine event-triggered control with MPC strategies, with the aim of reducing the frequency in solving optimization problems (see for instance Li and Shi (2014), Barradas Berglind et al. (2012)).

In the proposed approach the dynamic model adopted for the prediction is the Cell Transmission Model (CTM), a first order macroscopic model proposed by Daganzo (1994, 1995), properly rewritten as a Mixed Logical Dynamical (MLD) system, according to the framework proposed by Bemporad and Morari (1999). An MLD system is a dynamic system characterized by logic rules, on/off inputs, piecewise linear functions, discrete states, and can be expressed with linear equalities and inequalities in which continuous and binary variables are involved. In this work the CTM has been chosen for the prediction basically because the non-linearities present in its formulation are easily transformed in linear relations by adding some equalities and inequalities and some auxiliary variables. Nevertheless, the proposed event-triggered MPC scheme could be also adopted with other prediction models, in particular with other linearized traffic models, as for instance the one introduced by Groot et al. (2011), where the second-order METANET macroscopic traffic model is linearized, or the one by Sacone and Siri (2012) which is a piecewise version of the first-order macroscopic model.

The objective of the proposed control scheme is to penalize the situations in which the traffic densities exceed given threshold values and the queues at the on-ramps become positive (these two aspects will be properly weighted in the cost function of the FHOCP). Note that, the threshold values for the traffic density can be suitably determined depending on the specific purpose of the considered application, since they could be devised in order to maximize the outflow (and correspondingly to minimize the total time spent by vehicles in the freeway) or in order to pursue other objectives related, for instance, to environmental or safety aspects.

The paper is organized as follows. In Section 2 the CTM is outlined for the readers' convenience. Section 3 describes the prediction model used in the MPC scheme and reports the statement of the FHOCP. In Section 4 the proposed event-triggered MPC scheme is described in detail, whereas in Section 5 an accurate simulation analysis is reported. Finally, in Section 6 some conclusions are drawn.